MECHANICAL PROPERTIES OF ALUMINUM ALLOYS AT CRYOGENIC TEMPERATURES

MRG-190

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SUBJECT: Mechanical Properties of Aluminum Alloys at Cryogenic Temperatures

ABSTRACT: This report contains the mechanical property data obtained in the Materials Research Group on aluminum alloys at +78°F, -100°F, -320°F and -423°F. The data include tensile strengths, 0.2% offset yield strengths, elongations, notched tensile strengths, notched/unnotched tensile ratios on parent metal and tensile strengths, elongations and joint efficiencies of welded joints (heliarc butt welds and fusion welds with filler metal added). Materials tested include 2014-T6, 2024-T3, 2024-T4, 2219-T81, 2219-T87, 5052-H38, 5086-H34, 5086-H38, 5154-H38, 5456-H343, 6061-T4, 6061-T6, 7075-T6, 7079-T6, 7178-T6 and X7275-T6 sheet, 2024-T4, 6061-T6 and 7075-T6 plate and 7079-T6 billet material.

An analysis of the results is included for each alloy which primarily discusses the usefulness of the material for structural applications at cryogenic temperatures. Also, correlations of the material's mechanical properties are made with its chemistry, impurity content, microstructure, primary working and heat treatment. Recommendations are made concerning the use of aluminum alloys at cryogenic temperatures and future research work which has been suggested by this program.

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SUBJECT: Mechanical Properties of Aluminum Alloys at Cryogenic Temperatures

INTRODUCTION:

Very low temperatures are encountered in current and proposed missiles and space vehicles due to the use of cryogenic propellants such as liquid oxygen and liquid hydrogen (boiling points of -297°F and -423°F, respectively) and due to the near absolute zero temperatures encountered under certain conditions in outer space. Therefore, the properties of engineering materials at these extreme subzero temperatures are becoming of prime importance to the design engineer.

The primary purpose of this investigation was to determine the mechanical properties of a number of high-strength aluminum alloys in order to evaluate their usefulness for structural applications at cryogenic temperatures. Also, it was the prupose of this program to correlate the mechanical properties with such variables as chemistry, impurity content, microstructure, primary working, and heat treatment in order to better understand the mode of deformation and fracture characteristics of aluminum alloys as a function of temperature. Another purpose was to make definite recommendations for the future development of aluminum alloys in order to improve their properties at cryogenic temperatures. The materials tested in this program include 2014, 2024, 2219, 5052, 5083, 5086, 5154, 5456, 6061, 7075, 7079, 7178 and X7275 aluminum alloys in various tempers and degree of cold work and in several forms (sheet, plate and forging stock).

Many investigations have been made on the low temperature properties of aluminum alloys (Refs. 1, 2, 3, 4); however, in addition to the determination of tensile and elastic properties as a function of temperature, notched tensile properties and notched/unnotched tensile ratios were determined. The notched/unnotched ratios were determined as a function of temperature in order to evaluate the toughness, which is often referred to in terms of resistance to brittle fracture, or notch sensitivity (Refs. 5, 6, 7). A notched specimen with a stress concentration factor (K_t) of 6.3 was selected for use in this investigation because previous axial fatigue tests of complex welded joints and fatigue and burst tests of pressure vessels made of 301 extra full hard stainless steel exhibited excellent correlation with notched/unnotched tensile ratios obtained with this value of K_t over a range of temperatures from 78° to -423°F (Ref. 8). Data were obtained on specimens with less acute notches (e.g., K_t of 2.5-3.0) and were found to be less discriminatory between tough and brittle materials; in fact notched/unnotched ratios of near unity were obtained on some materials which were known to be brittle (Ref. 8). At the other extreme, however, stress concentration factors of 15 to 18 have been employed by some investigators (Ref. 4) and these tests in general tend to make all materials appear brittle. Thus, notched/unnotched tensile ratios using a K_t of 6.3 have proven to be both discriminatory between tough and brittle materials and to correlate with service behavior.

MATERIALS, TEST SPECIMENS AND APPARATUS:

The aluminum alloys used in this investigation and their history and chemical analyses are listed in Table 1. The tensile specimens used in this investigation are shown in Figure 1. All tensile specimens were inspected and individually measured for area determination. Notched specimens were inspected and measured by means of an optical comparator, and all specimens out of tolerance were rejected. The stress concentration factor (K_t) as determined by $\sqrt{\frac{\text{1/2 width between notches}}{\text{radius of the notch}}}$, was 6.3 with "in tolerance" limits of 5.7 to 7.1.

The testing apparatus consisted of a 50,000-lb. Baldwin universal testing machine equipped with a continuous stress-strain recorder and strain pacer. Standard extensometers were used at room temperature and a specially designed cryo-extensometer was used at low temperatures. Specially constructed cryostats were used for testing at sub-zero temperatures; a small open cryostat for -100° and -320°F, and a gas-tight cryostat insulated by a vacuum chamber, liquid nitrogen jacket and foamed polyurethane, for tensile testing at -423°F. A full description of the cryostat, cryo-extensometer, and accessory equipment, as well as the safety features and rapidity of testing can be found in Ref. 9. The tensile machine, extensometers and accessory equipment were periodically checked and calibrated.

EXPERIMENTAL PROCEDURE:

Tensile tests were performed at 78°F (room temperature), -100°F by immersion in a bath of dry ice and alcohol, -320°F by immersion in liquid nitrogen and -423°F by immersion in liquid hydrogen. Tests were conducted after the specimens came to temperature as determined by a copper-constantan thermocouple taped to the test section. Times required to reach temperature were from 2 to 5 minutes after immersion. The smooth tensile specimens were tested at a strain rate of 0.001 in./in./minute to yield, followed by a rate of 0.15 in./minute until fracture. Notched tensile specimens were tested at 0.001 in./in./minute, as determined by extensometers, until fracture. Yield strengths were determined from the continuous stress-strain curves by the 0.2% offset method. Elongations reported herein are total elongations as determined by scribe marks on a surface dye and read at 10X magnification over a 2-in. gage length for flat tensile specimens and a 1-in. gage length for the round test bars. Hardness measurements were made on a Rockwell superficial tester on the 15-N scale at room temperature.

EXPERIMENTAL RESULTS:

The tensile and yield strengths, elongations, notched tensile strengths, notched/unnotched tensile ratios and welded joint properties are presented in Tables II through XXII (see list of tables, page 11).

DISCUSSION OF RESULTS:

Each of the aluminum alloys will be discussed separately, particularly concerning its use for structural applications at cryogenic temperatures; however the behavior of pure aluminum at extreme sub-zero temperatures will be discussed first. Also, a few generalizations on the behavior of aluminum alloys at cryogenic temperatures will be made based upon the present test data.

The following may be said about the effects of low temperatures on the mechanical properties of metals, such as pure aluminum, which have face-centered, cubic lattice structures. (Refs. 10, 11) There is a small increase which is gradual and continuous in the initial resistance to deformation (yield strength) and in the elastic modulus as the temperature is lowered. There is little or no change in ductility as measured by elongation, from room to cryogenic temperatures. Also, there is no detrimental effect on toughness, as determined by impact tests, consequently, there is no ductile to brittle transition (such as is noted in many materials having body-centered cubic or hexogonal-close-packed structures). There is, however, a large increase (50 to 100%) in the tensile strength with reduction in temperature from +78°F to -423°F which is indicative that the hardness and possibly the rate of work hardening is strongly affected by temperature.

As may be seen from the data presented in Tables II through XXII, the aluminum alloys tested in this investigation do not behave in the same manner as pure aluminum at cryogenic temperatures. Yield strengths increase from 25 to 50% by reducing the temperature from +78°F to -423°F. Many of the alloys (7000 series) experienced a sharp decrease in ductility (as measured by elongation and reduction in area) at the lower temperatures. Notched tensile data and notched/unnotched tensile ratios indicate that many of the aluminum alloys (particularly some of the 5000 and 7000 series alloys) became embrittled at cryogenic temperatures. Tensile strengths increased from 25 to 50% instead of 50 to 100% as would be expected for pure aluminum.

Therefore it is seen that low temperatures affect the mechanical properties (yield and tensile strengths, ductility and toughness) of aluminum alloys quite differently as compared to undistorted crystals with face-centered cubic lattice structures. Explanations for the cryogenic behavior of these alloys is based upon the presence of a strained lattice structure, precipitates in the grain boundaries and slip planes, and intermetallic compounds. How large an effect these factors have on the behavior of aluminum alloys depends upon the type and amount of alloying elements and impurities present and whether they are in solid solution with the parent aluminum or in the form of a second phase.

The large increases in yield strength are felt to be due to the soild solution elements and precipitates within the crystal structure which create a strained or distorted lattice. Many of these strains within the lattice are "locked" in place at the lower testing temperatures thereby causing a large increase in the initial resistance to deformation (yield strength). The sharp decline in ductility of some of the 7000 series alloys is explained on the basis of "premature" fractures caused by stress concentrations (inclusions or large precipitates) within the grain and, or heavy precipitation at the grain boundaries which creates a brittle condition. Photomicrographs of fractured tensile specimens show these conditions (Ref. 12). The rate of work hardening for the aluminum alloys apparently was not strongly affected by decrease in temperature. This is shown by the fact that there was a smaller increase in tensile strength than is experienced in pure aluminum, that the hardness (15-N scale) of the fractured specimens near the fractures was nearly the same as for the untested material, and that slip lines appeared in only a few grains (Ref. 12). The decrease in toughness, as measured by the trend of the notched tensile strength and notched/unnotched tensile ratios, at the lower testing temperatures is felt to be due to the presence of a strained lattice and stress concentrators (precipitates and inclusions).

As may be seen from the data in Tables II through XXII, the 2000 and 6000 series alloys behave more like pure aluminum at cryogenic temperatures than do the 7000 series and the high Mg containing 5000 series alloys (5154 and 5456). This is explained on the basis that the total alloying content is much higher in the 7000 series and high Mg 5000 series alloys.

There appears to be a definite effect on the low temperature toughness as a result of various heat treatments. For example, the 6061-T6 alloy retains greater toughness than the 6061-T4 at -423°F; also the 2024-T4 remains tougher than 2024-T3. These data are explained on the basis that more of the alloying elements are precipitated out in the form of discrete particles of intermetallic compounds in the 6061-T6 and 2024-T4 than in the 6061-T4 and 2024-T3 which gives a less distorted lattice and therefore greater toughness for the 6061-T6 and 2024-T4 materials.

As witnessed by the data on 5086-H34 (half hard) and 5086-H38 (full hard), there is little effect as a result of the amount of working (cold rolling) in these alloys since both of these alloys retain about the same degree of toughness at cryogenic temperatures.

The notched/unnotched tensile ratios for the plate and billet materials were appreciably higher than for the corresponding sheet materials at room temperature. These data may be explained by the distortion energy theory

(Ref. 11), which also explains why notched/unnotched tensile ratios greater than unity may be obtained. The distortion energy theory states that the total stress-strain curve (elastic and plastic regions) is raised under conditions of biaxial loading and even more so for triaxial loading than for simple tension. Therefore, due to the biaxial loading present in notched sheet specimens and triaxial loading in notched bar specimens, it is possible to obtain notched/unnotched values of 1.1 and 1.3, respectively. For this reason a comparison of data obtained from flat specimens (sheet material) and round specimens (plate material) is not attempted.

2000 SERIES ALUMINUM ALLOYS:

Based on the notched tensile strengths and notched/unnotched tensile ratios, it is felt that the following 2000 series aluminum alloys may be used for structural applications at -423°F: 2014-T6, 2024-T4, 2219-T81 and 2219-T87 sheet and 2024-T4 plate. 2024-T3 sheet may be used to -320°F. Table XXIII is a Material Selection Guide which indicates at which temperatures the aluminum alloys tested in this investigation may be used for structural applications.

Of the 2000 series alloys, 2014-T6 has the highest strength (60 + ksi F_{ty} and 70 + ksi F_{tu} at 78°F) with an appreciable increase in tensile properties at cryogenic temperatures (80 + ksi F_{ty} and 100 + ksi F_{tu} at -423°F). Elongation of the base metal remains uniform at all testing temperatures. Welded joints (manually welded by the tungsten arc method with 2319 filler metal, tested with bead in place) are 70 + % efficient at all testing temperatures. Elongations of welded joint specimens were low (2% at 78°F and 1.2% at -423°F); however there was no indication of embrittlement in the weld or heat affected zone as determined by notched tensile tests. Further information (e.g. cost, availability, formability, etc.) on 2014-T6 is available in MRG-192-2.

2219-T81 and -T87 are the next higher strength 2000 series alloys. 2219 was recently developed as a high temperature alloy; however it shows great promise for cryogenic applications. Weld joint efficiencies and elongations are simular for 2219 as they were for the 2014-T6 alloy. 2024-T4 in both sheet and plate remains tough to -423°F; however this alloy is of lower strength. The toughness of 2024-T3 is questionable at -423°F. 2024-T3 is not recommended for structural applications which must withstand high stresses or impact loading at -423°F.

At the present time there is a paucity of fatigue data on aluminum alloys at cryogenic temperatures, particulary on welded joints and at high stress levels. It is felt that fatigue data should be obtained on those alloys which appear to be the most promising for cryogenic applications.

5000 SERIES ALUMINUM ALLOYS

Of the 5000 series aluminum alloys, 5052-H38 and 5083-H38 appear to remain tough enough for structural applications at -423°F. 5086-H34 and -H38 and 5154-H38 may be used to -320°F. Notched tensile data indicate that 5456-H343 suffers some degree of embrittlement even at -100°F; therefore this alloy is not recommended for cryogenic applications.

Of the two 5000 series alloys acceptable for use at -423°F the 5083-H38 has the highest strength (see Table IX); however this material was experimentally rolled to the H38 temper. It is felt that this material should be more thoroughly evaluated before being used at -423°F. Data obtained on welded joints (heliarc butt weld, roll planished, no filler metal) are presented in Tables VIII, X, XII and XIII for 5052-H38, 5086-H34, 5154-H38 and 5456-H343. Welded joint efficiencies ranged from about 65 to 85% depending upon the material and testing temperature. Base metal and weld elongations generally increased with reduction in temperature. As was mentioned previously, the poor toughness of some of the 5000 series alloys (e.g. 5456) is felt to be due to the highly strained lattice resulting from the large amount of alloying content in solid solution or precipitated in the crystal structure. At the present time more information is available on the 5052 alloy (see MRG-192-2); therefore it is recommended for use at -423°F in preference to 5083 until further data may be obtained.

6000 SERIES ALUMINUM ALLOYS

6061-T6 sheet and plate remain sufficiently tough for structural applications to -423°F. 6061-T4 appears to become embrittled at the lower testing temperatures and is not recommended for use at -423°F. The strength of 6061 is significantly less than other aluminum alloys (e.g. 2014) which remain tough to -423°F. Weld data were not obtained.

7000 SERIES ALUMINUM ALLOYS

The notched tensile strengths which indicate notch sensitivity and the notched/unnotched tensile ratios which may be used as indices for resistance to brittle fracture show that all the 7000 series aluminum alloys suffer a degree of embrittlement at very low temperatures. As may be seen in Tables XVII through XXII, notched/unnotched tensile ratios are considerably less than unity for 7178 at -100°F, for 7075, 7275 and 7178 at -320°F and for all of the 7000 series aluminum alloys at -423°F.

The poor toughness, as measured by the notched/unnotched tensile ratio, of these alloys at cryogenic temperature is felt to be primarily due to the chemistry (high alloying content) and to the impurities present. The toughness of the 6000, 5000 and 2000 series aluminum alloys, representing low alloying, magnesium alloying, and copper alloying, respectively, is not as severely impaired at low temperatures (Refs. 1, 3, 4, 8) as for the 7000 series alloys. Therefore, it appears that the high alloying (Zn, Mg, Cu) contents, and in particular, the zinc additions are primarily responsible for the low temperature embrittlement. Further evidence of this effect may be seen by comparing the chemistry of 7079 sheet material which has nearly the same total alloying content but much smaller amounts of zinc and copper, with the rest of the 7000 series alloys. This alloy retains greater toughness at much lower temperatures than the 7075, 7275 or 7178 alloys. That impurity content is a factor controlling low temperature embrittlement is apparent from the fact that 7275-T6 retains greater toughness to -320°F than 7075-T6. As may be seen in Table 1, 7275 is merely a high purity 7075 alloy and as such has far fewer inclusions present in the microstructure. Also, the abnormally low transverse properties of 7075-T6 plate may be explained due to the large number of inclusions present in the grain boundaries.

The second important factor effecting low temperature embrittlement of the 7000 series aluminum alloys is that of primary working. The degree of primary working of the metal is important as may be seen by comparing the properties of the 7079-T6 sheet and 7079-T6 billet material. Chemistries were nearly identical; however, the billet material experienced much more severe embrittlement at lower temperatures than the sheet material. This may be explained by the cored structure present in the 7079-T6 billet, which was not broken up by primary working.

Based upon the data obtained in this investigation, it is recommended that extreme caution be exercised in employing any of the 7000 series alloys for low temperature structural applications in which high stresses and impact loading are present. In fact; it is recommended that none of these alloys be used for such applications below -320°F, that only 7079-T6 sheet material be employed at less than -100°F, and that 7178-T6 sheet material not be used much below room temperature. These recommendations are based upon present information; however it is felt that future development may considerably improve the low temperature properties of these alloys. In view of the above mentioned factors which effect low temperature embrittlement, it is suggested that further development of the 7000 series alloys for the purpose of improving their cryogenic properties be concerned with chemistry, impurity content, and degree of primary working. Research along these lines is presently being initiated in the Materials Research Group.

RECOMMENDATIONS:

Based upon the data obtained in this investigation, the following aluminum alloys may be used for structural applications at -423°F: 2014-T6, 2024-T4, 2219-T81, 2219-T87, 5052-H38, 5083-H38 and 6061-T6 sheet and 2024-T4 and 6061-T6 plate. These alloys as well as the following alloys may be used for structural applications down to -320°F: 2024-T3, 5086-H34, 5086-H38, 5154-H38, 6061-T4 and 7079-T6 sheet. Two of the aluminum alloys tested are not recommended for use at any sub-zero temperature (5456-H343 and 7178-T6). Table XIII is a Material Selection Guide which is added for convenience in selecting those alloys which may be used at extreme sub-zero temperatures. These recommendations are based upon present data which was generally obtained on only one lot (heat) aluminum for each alloy; therefore further testing (tensile, notched tensile and fatigue) should be conducted before using the above mentioned alloys in a major structure at cryogenic temperatures.

In addition to further evaluation of the more promising alloys, it is felt that more research should be conducted to further determine the effects of chemistry, impurities, microstructure, primary working and heat treatment on the properties of aluminum alloys at cryogenic temperatures. The purpose of this research is to develop aluminum alloys of higher strength commensurate with adequate toughness for use at cryogenic temperatures.

CONCLUSIONS:

1. Based upon notched tensile strengths and notched/unnotched tensile ratios, the following aluminum alloys may be used for structural applications at -423°F: 2014-T6, 2024-T4, 2219-T81, 2219-T87, 5052-H38, 5083-H38 and 6061-T6 sheet and 2024-T4 and 6061-T6 plate.

2. In addition to the above mentioned alloys, 2024-T3, 5086-H34, 5086-H38, 5154-H38, 6061-T4 and 7079-T6 sheet may be used to -320°F.

3. 7075-T6 sheet and plate and X7275-T6 sheet may be used to -100°F; 5456-H343 and 7178-T6 sheet should not be used at any sub-zero temperature (-100°F or below).

4. In general, the mechanical properties of aluminum alloys are affected quite differently as compared to the mechanical properties of pure aluminum at cryogenic temperatures.

5. The large increases in yield strengths of aluminum alloys with reduction in temperature is felt to be due to the strained lattice created by alloying elements, impurities and precipitates within the crystal.

6. The sharp reduction in ductility noted for some of the 7000 series alloys at -320°F and at -423°F is felt to be due to "premature" fractures caused by stress concentrators (inclusions and large precipitates) and brittle grain boundaries (caused by heavy precipitation in the grain boundaries).

7. Aluminum alloys experienced less work hardening at cryogenic temperatures than pure aluminum, as determined by relatively small increases in F_{tu}, little or no increase in hardness and the appearance of only a few slip lines in the microstructures of fractured specimens.

8. The decrease in toughness in some of the aluminum alloys at reduced temperatures is felt to be due to one or more of the following: strained lattice, stress concentrators (inclusions, etc.) and brittle grain boundaries.

9. Notched/unnotched tensile ratios on round (bar) specimens are not the same as for flat (sheet) specimens. The explanation is based on the distortion energy theory.

10. There appears to be a definite effect of various heat treatments on the toughness of several alloys at cryogenic temperatures. This is explained on the basis of the degree of strain within the lattice as a result of the amount of alloying elements in solid solution.

11. There seems to be little or no effect (within the limits tested) of the amount of primary working (cold rolling) upon the toughness of the 5000 series alloys at cryogenic temperatures. However, as seen by the data on 7079-T6 billet material, sufficient working to break up the cored (as cast) structure is required to improve the toughness at cryogenic temperatures.

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TABLE I

History and Chemical Analysis of Aluminum Alloys

MATERIAL TEMPER - FORM	GAUGE (in.)	SPECIFICATION OR HEAT NO.	SUPPLIER	CHEMISTRY Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn
2014-T6 Sheet	0.063	AMS 4029	Alcoa	-	4.37	0.36	0.23	0.62	0.69	0.018	-
2024-T3 Sheet	0.025	QQ-A-355	Alcoa	0.01	4.80	0.32	1.46	0.55	0.19	0.02	0.21
2024-T4 Sheet	0.032	QQ-A-355	Alcoa	-	4.35	0.31	1.34	0.51	0.15	0.015	-
2024-T4 Plate	2.0	QQ-A-355	Alcoa	0.01	4.83	0.73	1.84	0.92	0.26	0.02	0.25
2219-T81 Sheet	0.063		Alcoa	-	5.8	0.10	0.01	0.29	0.1	0.066	-
2219-T87 Sheet	0.063		Alcoa	-	6.0	0.15	0.01	0.37	0.1	0.068	-
5052-H38 Sheet	0.040	635-521	Alcoa	0.172	0.045	0.249	2.59	-	0.11	0.011	-
5083-H38 Sheet	0.050	Experimental	Kaiser	0.12	0.04	0.14	4.50	0.80	0.11	0.02	0.04
5086-H34 Sheet	0.040	106-404	Alcoa	0.11	0.05	0.18	3.66	0.37	0.11	0.01	-
5086-H38 Sheet	0.050	Experimental	Kaiser	0.15	0.04	0.27	3.93	0.45	0.12	0.02	0.06
5154-H38 Sheet	0.040	667-471	Alcoa	0.21	0.03	0.22	3.38	-	0.12	0.10	-
5456-H343 Sheet	0.050	Mil-A19842	Alcoa	0.08	0.06	0.22	5.27	0.81	0.13	0.02	0.03
6061-T4 Sheet	0.025	QQ-A-327	Kaiser	0.19	0.15	0.50	0.95	0.09	0.56	0.03	0.17
6061-T6 Sheet	0.020	QQ-A-327	Kaiser	0.18	0.23	0.37	0.94	0.08	0.76	0.06	0.05
6061-T6 Plate	1.0	QQ-A-327	Kaiser	0.37	0.28	0.66	1.23	0.08	0.83	0.02	0.10
7075-T6 Sheet	0.025	QQ-A-283	Alcoa	0.23	1.47	0.32	2.45	0.04	0.15	0.05	5.85
7075-T6 Plate	2.5	QQ-A-283	Kaiser	0.185	1.43	0.25	2.75	0.044	0.14	0.039	5.46
7079-T6 Sheet	0.080		Kaiser	0.16	0.64	0.12	3.46	0.20	0.14	0.03	4.34
7079-T6 Billet	5.0	0-01041	Alcoa	0.13	0.71	-	3.30	0.14	0.1	0.06	4.15
7178-T6 Sheet	0.036	Mil-A-9180A	Kaiser	0.26	1.95	0.21	3.0	0.04	0.11	0.02	6.6
X7275-T6 Sheet	0.050	Experimental	Kaiser	0.17	1.58	0.04	2.70	0.04	0.05	0.04	5.74

TABLE II

Mechanical Properties of 2014-T6 Aluminum Alloy

0.063" Sheet, Alcoa, AMS 4029

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	e %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/ UNNOTCHED TENSILE RATIO	WELD TENSILE* STRENGTH (ksi)	WELD ELONG %	JOINT EFF %
+78	Long.	66.3	73.7	11	74.8		51.2	2.0	
	Long.	65.1	72.5	11	74.1		54.8	2.0	
	Long.						53.4	1.5	
	Avg	65.7	73.1	11	74.5	1.02	53.1	2.0	73
+78	Trans.	62.5	71.4	11	70.9				
	Trans.	63.0	71.9	11	71.6				
	Trans.	63.0	71.3	11	67.5				
	Avg	62.8	71.5	11	70.0	0.98			
-100	Long.	69.2	76.5	12	79.6		55.8	1.5	
	Long.	69.3	76.3	12	78.7		58.8	2.5	
	Long.						55.5	1.5	
	Avg	69.3	76.4	12	79.2	1.04	56.7	2.0	74
-100	Trans.	64.5	74.6	12	71.5				
	Trans.	64.8	74.1	11	70.3				
	Trans.	63.6	73.5	11	71.2				
	Avg	64.3	74.1	11	71.0	0.96			
-320	Long.	74.4	87.4	14	85.3		60.9	1.0	
	Long	-	86.8	14	85.6		63.2	1.0	
	Long.						61.6	1.0	
	Avg	74.4	87.1	14	85.5	0.98	61.9	1.0	71
-320	Trans.	71.8	85.1	14	79.8				
	Trans.	66.6	79.7	14	75.9				
	Trans.	72.6	86.1	13	80.3				
	Avg	70.3	78.7	14	78.7	1.00			
-423	Long.	87.4	105	18	100		71.7	1.0	
	Long.	85.0	103	16	95.5		83.6	1.0	
	Long.						71.4	1.5	
	Avg	86.2	104	17	97.8	0.94	75.6	1.2	73
-423	Trans.	80.2	101	15	85.4				
	Trans.	83.5	104	15	86.3				
	Trans.	83.2	101	15	81.8				
	Avg	82.3	102	15	84.5	0.83			

*Filler Metal (2319) weld, tested with bead in place.

TABLE III

Mechanical Properties of 2024-T3 Aluminum Alloy

0.025" Sheet, Alcoa, QQ-A-355

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	47.8	67.8	18	59.9	
	Long.	47.5	68.1	18	59.8	
	Long.	47.0	67.9	18	60.8	
	Ave.	47.4	67.9	18	60.2	0.89
+78°F	Trans.	43.8	66.2	18	62.6	
	Trans.	43.9	65.4	18	63.1	
	Ave.	43.9	65.8	18	62.9	0.96
-100°F	Long.	49.4	70.3	21	60.0	
	Long.	49.2	70.5	21	61.2	
	Long.	48.1	69.9	20	62.3	
	Ave.	48.9	70.2	21	61.2	0.87
-100°F	Trans.	44.0	67.9	21	62.7	
	Trans.	45.0	67.7	21	62.8	
	Ave.	44.5	67.8	21	62.8	0.93
-320°F	Long.	61.0	86.1	22	76.6	
	Long.	61.4	87.8	22	76.6	
	Long.	60.2	87.2	22	75.4	
	Ave.	60.9	87.0	22	76.2	0.88
-320°F	Trans.	56.5	83.2	22	75.4	
	Trans.	55.7	83.5	22	73.9	
	Ave.	56.1	83.4	22	74.7	0.90
-423°F	Long.	-	109	19	88.3	
	Long.	70.9	110	14	84.8	
	Long.	75.2	112	19	95.2	
	Long.				86.7	
	Ave.	73.1	110	17	88.8	0.81
-423°F	Trans.	68.9	106	19	85.4	
	Trans.	69.0	107	17	88.2	
	Ave.	69.0	107	18	86.8	0.81

TABLE IV

Mechanical Properties of 2024-T4 Aluminum Alloy

0.032" Sheet, Alcoa, QQ-A-355

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	42.6	67.5	19	58.3	
	Long.	42.9	66.9	19	59.2	
	Long.	43.0	68.6	18	59.5	
	Ave.	42.8	67.7	19	59.0	0.87
+78°F	Trans.	40.5	64.8	20	57.5	
	Trans.	42.4	69.4	20	57.5	
	Ave.	41.5	67.1	20	57.5	0.86
-100°F	Long.	43.0	70.1	24	60.1	
	Long.	44.1	69.6	20	60.4	
	Long.	44.1	69.6	21	61.7	
	Ave.	43.7	69.8	22	60.7	0.87
-100°F	Trans.	42.4	67.2	25	58.9	
	Trans.	43.0	68.8	23		
	Ave.	42.7	68.0	24	58.9	0.87
-320°F	Long.	54.8	86.0	32	71.3	
	Long.	55.0	83.9	24	71.2	
	Long.	52.4	84.8	24	73.3	
	Ave.	54.1	84.9	27	71.9	0.85
-320°F	Trans.	53.7	81.3	16	65.7	
	Trans.	53.5	82.2	21	70.6	
	Ave.	53.6	81.8	19	68.2	0.83
-423°F	Long.	74.3	103	12	85.3	
	Long.	74.8	108	19	86.9	
	Long.	70.9	110	17	91.2	
	Long.				89.8	
	Ave.	73.3	107	16	88.3	0.83
-423°F	Trans.	66.8	94.3	10	85.6	
	Trans.	68.2	99.8	10	85.1	
	Ave.	67.5	97.1	10	85.4	0.83

TABLE V

Mechanical Properties of 2024-T4 Aluminum Alloy

2.0" Plate, Alcoa, QQ-A-355

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	e %	R. A. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long	56.7	71.5	19	12	82.4	
	Long.	53.6	67.9	22	22	79.6	
	Long.	53.3	70.0	21	18	84.8	
	Ave.	54.5	69.8	21	17	82.3	1.18
+78°F	Trans.	45.3	66.3	16	15	77.2	
	Trans.	45.7	67.5	16	15	75.3	
	Trans.					76.0	
	Ave.	45.5	66.9	16	15	76.2	1.14
-100°F	Long.	55.3	69.6	19	4	84.1	
	Long.	56.0	69.1	16	2	84.2	
	Long.	55.0	71.9	21	5	82.8	
	Ave.	55.4	70.2	19	4	83.7	1.19
-100°F	Trans.	-	65.3	-	5	80.4	
	Trans.	45.2	67.4	16	12	74.4	
	Ave.	45.2	66.4	16	9	77.4	1.17
-320°F	Long.	65.9	81.5	13	11	95.4	
	Long.	67.4	81.7	6	12	96.6	
	Long.	-	83.7	16	11	100	
	Ave.	66.7	82.3	12	11	97.3	1.18
-320°F	Trans.	50.7	80.7	17	12	90.3	
	Trans.	-	80.4	12	-	89.4	
	Ave.	50.7	80.6	15	12	89.9	1.12
-423°F	Long.	79.9	95.5	8	5	112	
	Long.	80.1	95.8	13	10	111	
	Long.	79.9	95.0	10	12	110	
	Ave.	80.0	95.4	10	9	111	1.16
-423°F	Trans.					95	
	Trans.	69.4	93.6	8	9	95	
	Ave.	69.4	93.6	8	9	95	1.01

TABLE VI

Mechanical Properties of 2219-T81 Aluminum Alloy

0.063" Sheet, Alcoa

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	e %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/ UNNOTCHED TENSILE RATIO	* WELD TENSILE* STRENGTH (ksi)	WELD ELONG (%)	JOINT EFF (%)
+78°F	Long.	52.0	67.4	10	64.1	0.95	47.7	2	
	Long.	51.9	67.6	9	64.7		48.7	3	
	Long.						48.0	3	
	Ave.	52.0	67.5	10	64.4	0.95	48.1	3	71
+78°F	Trans.	51.0	67.2	10	63.0				
	Trans.	51.0	67.2	10	69.0				
	Ave.	51.0	67.2	10	66.0	0.98			
-100°F	Long.	56.5	73.0	9	68.4		50.2	6	
	Long.	56.9	73.5	9	68.8		49.5	4	
	Long.						49.5	4	
	Ave.	56.7	73.3	9	68.6	0.94	49.7	5	68
-100°F	Trans.	54.7	72.2	11	67.1				
	Trans.	54.7	72.3	9	66.8				
	Ave.	54.7	72.3	10	67.0	0.93			
-320°F	Long.	61.7	85.1	11	72.2		63.7	2	
	Long.	62.7	85.3	11	77.5		63.6	2	
	Long.						65.7	4	
	Ave.	62.2	85.2	11	77.4	0.91	64.3	3	75
-320°F	Trans.	61.4	84.6	12	76.7				
	Trans.	-	84.6	12	75.4				
	Ave.	61.4	84.6	12	76.1	0.90			
-423°F	Long.	69.0	100	15	92.3		73.2	2	
	Long.	72.2	103	15	94.5		71.5	2	
	Long.						72.4	2	
	Ave.	70.6	102	15	93.4	0.92	72.4	2	71
-423°F	Trans.	66.8	101	15	94.6				
	Trans.	68.2	102	15	88.0				
	Ave.	67.5	102	15	91.3	0.90			

* Manually welded with 2319 aluminum filler metal, no post heat treatment, tested with bead in place (all fractures occurred in heat effected zone).

TABLE VII

Mechanical Properties of 2219-T87 Aluminum Alloy

0.063" Sheet, Alcoa

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	e %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/* UNNOTCHED TENSILE RATIO	WELD TENSILE STRENGTH (ksi)	WELD ELONG (%)	JOINT EFF (%)
+78°F	Long.	58.3	70.8	9	68.9		50.6	2	
	Long.	58.0	70.6	9	70.5		50.0	2	
	Long.						52.6	3	
	Ave.	58.2	70.7	9	69.7	0.99	51.1	2	72
+78°F	Trans.	58.5	71.1	9	70.6				
	Trans.	58.6	71.1	9	68.8				
	Ave.	58.6	71.1	9	69.7	0.98			
-100°F	Long.	62.4	76.6	9	75.0		50.6	5	
	Long.	62.3	76.1	9	74.2		48.5	3	
	Long.						49.5	3	
	Ave.	62.4	76.4	9	74.6	0.98	49.5	4	65
-100°F	Trans.	61.9	76.4	9	74.8				
	Trans.	63.7	76.3	9	72.5				
	Ave.	62.8	76.4	9	73.7	0.96			
-320°F	Long.	69.4	88.6	11	85.9		61.0	2	
	Long.	70.0	88.2	11	85.0		60.9	2	
	Long.						61.8	2	
	Ave.	69.7	88.4	11	85.5	0.97	61.2	2	69
-320°F	Trans.	70.8	89.3	11	83.6				
	Trans.	70.0	89.4	11	83.8				
	Ave.	70.4	89.4	11	83.7	0.94			
-423°F	Long.	76.6	104	14	95.1		76.4	1.5	
	Long.	76.2	104	14	96.0		70.7	0.5	
	Long.						71.8	0.5	
	Ave.	76.4	104	14	95.6	0.92	73.0	1	70
-423°F	Trans.	76.2	105	14	95.1				
	Trans.	75.6	105	14	95.2				
	Ave.	75.9	105	14	95.2	0.91			

* Manually welded with 2319 aluminum filler metal, no post heat treatment, tested with bead in place (all fractures occurred in heat effected zone).

TABLE VIII

Mechanical Properties of 5052-H38 Aluminum Alloy

.040" Sheet, Alcoa, Heat No. 635-521

TEST TEMP. °F	DIRECTION	F_{ty} ksi	F_{tu} ksi	e %	NOTCHED T.S. ksi (K_t=6.3)	NOTCHED/ UNNOTCHED TENSILE RATIO	HELIARC* BUTT WELD T.S. ksi	WELD ELONG %	JOINT EFF %
+78	Long.	39.7	44.8	7	48.5		30.0	3	
	Long.	40.1	45.2	7	48.1		30.0	3	
	Long.	39.9	45.0	8	48.4		30.0	3	
	Long.	40.5	45.4	7			30.6	4	
	Long.	40.0	45.3	7			30.5	3	
	Avg	40.0	45.1	7	48.3	1.07	30.2	3	67
+78	Tran.	41.1	45.7	9	50.6				
	Tran.	41.9	46.0	9	51.9				
	Tran.				51.2				
	Tran.				50.8				
	Tran.				51.2				
	Avg	41.5	45.9	9	51.1	1.11			
-100	Long.	41.1	47.3	11	50.6		31.4	5	
	Long.	40.7	46.9	11	50.4		32.2	4	
	Long.	41.1	47.1	10			31.7	5	
	Avg.	41.0	47.0	11	50.5	1.07	31.8	4	68
-100	Tran.	41.1	47.2	11	54.2				
	Tran.	42.8	47.9	11	54.1				
	Avg	42.0	47.0	11	54.2	1.13			
-320	Long.	48.7	63.4	24	63.1		45.8	5	
	Long.	48.0	62.4	27	63.2		47.9	5	
	Long.		62.3	18	63.5		46.2	6	
	Long.	47.7	62.8	26			46.9	5	
	Long.	47.6	62.3	30			47.0	5	
	Avg	48.0	62.6	25	63.3	1.01	46.8	5	75
-320	Tran.		59.1	26	64.2				
	Tran.	47.9	58.8	25	63.5				
	Tran.				64.4				
	Tran.				64.0				
	Tran.				64.3				
	Avg	47.9	59.0	26	64.1	1.09			
-423	Long.	54.3	91.2	30	81.0		59.7	7	
	Long.	54.8	88.9	32	81.0		66.5	9	
	Long.	54.9	89.0	32	79.8		57.1	7	
	Long.						72.1	10	
	Long.						69.2	9	
	Avg	54.7	89.7	32	80.6	.90	64.9	9	72
-423	Tran.	56.5	79.7	35	77.7				
	Tran.		82.4	38	78.7				
	Avg	56.5	81.2	37	78.2	.96			

*Heliarc butt weld; x-rayed; roll planished; no doubler reinforcement

TABLE IX

Mechanical Properties of 5083-H38 Aluminum Alloy

0.050" Sheet, Kaiser, Experimental Heat

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	e %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	57.1	62.5	5	61.8	
	Long.	56.2	62.9	5	62.4	
	Ave.	56.7	62.7	5	62.1	0.99
+78°F	Trans.	55.5	65.0	8	64.5	
	Trans.	56.1	65.2	9	64.0	
	Ave.	55.8	65.1	9	64.3	0.99
-320°F	Long.	65.0	82.4	16	76.7	
	Long.	65.0	81.7	13	77.0	
	Ave.	65.0	82.1	15	76.9	0.94
-320°F	Trans.	65.1	80.8	17	76.7	
	Trans.	64.1	80.3	14	78.2	
	Ave.	64.6	80.6	16	77.5	0.96
-423°F	Long.	71.5	99.2	12	86.7	
	Long.	-	102	13	87.4	
	Ave.	71.5	101	13	87.1	0.86
-423°F	Trans.	72.6	95.2	12	90.5	
	Trans.	79.1	98.7	12	84.1	
	Ave.	75.9	97.0	12	87.3	0.90

TABLE I

Mechanical Properties of 5086-H34 Aluminum Alloy

.040" Sheet, Alcoa, Heat No. 106-404

TEST TEMP. °F	DIRECTION	F_{ty} ksi	F_{tu} ksi	e %	NOTCHED T.S. ksi (K_t=6.3)	NOTCHED/UNNOTCHED TENSILE RATIO	HELIARC* BUTT WELD T.S. ksi	WELD ELONG %	JOINT EFF %
+78	Long.	35.3	47.6	10	48.7		38.5	3	
	Long.	35.8	48.0	8	48.7		38.3	4	
	Long.		47.3	10	48.6		40.0	4	
	Long.	36.0	48.1	9			39.0	4	
	Long.	35.7	48.1	9			39.4	4	
	Avg	35.7	47.8	9	48.7	1.02	39.0	4	82
+78	Tran.	32.8	47.1	15	47.1				
	Tran.	33.0	46.6	14	47.0				
	Tran.				46.7				
	Tran.				46.5				
	Avg	32.9	46.9	15	46.8	1.00			
-100	Long.	36.5	48.7		50.3		39.5	5	
	Long.	36.6	49.0	15	50.2		39.9	5	
	Long.	36.7	48.9	15			39.0	5	
	Avg	36.6	48.9	15	50.3	1.03	39.5	5	81
-100	Tran.	32.4	47.7	15	47.4				
	Tran.	33.5	47.5	15	47.8	1.00			
-320	Long.	41.5	66.1	24	62.7		57.4	9	
	Long.	40.5	66.0	28	62.0		57.5	8	
	Long.	41.3	63.6		61.0		56.4	9	
	Long.	40.9	66.0	20			54.9	9	
	Long.	40.0	65.1	23			55.7	9	
	Avg	40.8	65.4	24	61.9	.95	56.4	9	86
-320	Tran.	37.2	61.6	27	54.7				
	Tran.	38.1	62.2	29	54.9				
	Tran.				55.1				
	Tran.				55.2				
	Avg	37.7	61.9	28	55.0	.89			
-423	Long.	46.7	96.7	31	75.0		75.9	11	
	Long.	47.7	96.5	31	68.8		76.3	11	
	Long.	46.6	92.7	27	70.3		74.1	11	
	Long.						74.9	11	
	Avg	47.0	95.3	30	71.4	.75	75.3	11	79
-423	Tran.	44.9	86.4	36	58.3				
	Tran.	43.4	84.9	24	58.4				
	Avg	44.2	85.7	30	58.4	.68			

*Heliarc butt weld; x-rayed; roll planished; no doubler reinforcement

TABLE XI

Mechanical Properties of 5086-H38 Aluminum Alloy

0.050" Sheet, Kaiser, Experimental Heat

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	57.4	64.3	6	65.2	
	Long.	58.5	64.1	7	63.9	
	Long.	58.8	64.2	7	64.8	
	Ave.	58.2	64.2	7	64.6	1.01
+78°F	Trans.	56.5	65.8	9	69.0	
	Trans.	56.8	66.0	9		
	Ave.	56.7	65.9	9	69.0	1.05
-100°F	Long.	-	66.2	12	66.7	
	Long.	58.6	66.2	9	67.5	
	Long.	58.1	66.2	8	68.2	
	Ave.	58.4	66.2	10	67.5	1.02
-100°F	Trans.	58.4	67.7	10	71.9	
	Trans.	56.1	67.5	10		
	Ave.	57.3	67.6	10	71.9	1.06
-320°F	Long.	59.5	76.1	19	75.4	
	Long.	61.8	76.9	19	75.2	
	Long.	61.4	77.3	17	75.3	
	Ave.	60.9	76.8	18	75.3	0.98
-320°F	Trans.	68.3	81.6	17	80.0	
	Trans.	65.5	81.2	17		
	Ave.	66.9	81.4	17	80.0	0.98
-423°F	Long.	-	106	24	85.1	
	Long.	69.1	101	25	77.3	
	Long.	82.1	107	25	81.0	
	Ave.	75.6	105	25	81.1	0.77
-423°F	Trans.	65.5	92.4	25	85.3	
	Trans.	67.0	92.8	27		
	Ave.	66.3	92.6	26	85.3	0.92

TABLE XII

Mechanical Properties of 5154-H38 Aluminum Alloy

.040" Sheet, Alcoa, Heat No. 667-471

TEST TEMP °F	DIRECTION	F_{ty} ksi	F_{tu} ksi	e %	NOTCHED T.S. ksi (K_t=6.3)	NOTCHED/ UNNOTCHED TENSILE RATIO	HELIARC* BUTT WELD T.S. ksi	WELD ELONG %	JOINT EFF %
+78	Long.	40.0	47.8	9	49.7		33.9	3	
	Long.	40.2	47.7	9	49.5		36.6	3	
	Long.	40.4	47.4	9	49.5		35.6	2	
	Long.						36.7	3	
	Long.						35.1	3	
	Avg	40.2	47.6	9	49.5	1.04	35.7	3	75
+78	Tran.	40.6	49.2	15	54.0				
	Tran.	40.5	49.1	13	54.0				
	Avg	40.6	49.2	14	54.0	1.10			
-100	Long.	40.9	49.2	14	51.2		38.4	2	
	Long.	40.6	49.4	13	51.1		38.8	2	
	Avg	40.8	49.3	14	51.2	1.04	38.6	2	78
-100	Tran.	41.7	50.1	15	55.3				
	Tran.	40.9	50.3	15	55.4				
	Avg	41.3	50.2	15	55.4	1.21			
-320	Long	47.3	66.5	30	64.3		53.8	7	
	Long.	47.2	66.1	30	64.3		53.8	7	
	Long.	46.8	66.0	30	64.4		55.0	8	
	Long.						55.2	7	
	Long.						54.7	8	
	Avg	47.1	66.2	30	64.3	.97	55.5	7	84
-320	Tran.	47.0	63.8	29	66.0				
	Tran.	47.1	63.4	30	66.2				
	Avg	47.1	63.6	30	66.1	1.04			
-423	Long.	53.4	93.4	38	76.9		77.2	11	
	Long.	54.6	93.1	31	78.7		74.5	11	
	Long.	54.1	93.9	36	77.1		75.6	11	
	Avg	54.0	93.5	35	77.6	.83	75.8	11	81
-423	Tran.	57.0	88.0	37	76.5				
	Tran.	55.9	93.0	39	77.8				
	Avg	56.5	91.0	38	77.2	.85			

*Heliarc butt weld; roll planished; no doubler reinforcement

TABLE XIII

Mechanical Properties of 5456-H343 Aluminum Alloy

0.050" Sheet, Alcoa, Mil-A 19842

TEST TEMP. °F	DIRECTION	F_{ty} ksi	F_{tu} ksi	e %	NOTCHED T.S. ksi (K_t=6.3)	NOTCHED/ UNNOTCHED TENSILE RATIO	HELIARC* BUTT WELD T.S. ksi	WELD ELONG %	JOINT EFF %
+78	Long.	47.9	59.5	6.5	54.3		49.6	8.0	
	Long.	46.5	58.3	6.5	53.6		47.1	3.0	
	Long.	47.2	58.1	6.5	54.6		46.0	2.0	
	Avg	47.2	58.6	6.5	54.2	0.92	47.6	4.3	81
+78	Trans.	44.4	59.3	9.0	54.0		47.1	3.0	
	Trans.	46.3	61.5	8.5	51.6		47.6	3.0	
	Avg	45.4	60.4	8.7	52.8	0.87	47.4	3.0	78
-100	Long.	48.1	59.8	8.5	47.9		47.6	2.5	
	Long.	47.8	59.8	8.5	53.1		50.0	3.0	
	Long.	47.6	59.7	8.0			49.9	3.0	
	Avg	47.8	59.8	8.3	50.5	0.84	49.2	2.8	82
-100	Trans.	44.8	61.2	9.5	50.0		51.6	3.5	
	Trans.	46.1	61.2	9.0	46.4		52.1	4.0	
	Trans.				49.8				
	Avg	45.5	61.2	9.2	48.7	0.80	51.9	3.7	85
-320	Long.	53.2	72.4	8.0	50.9		67.1	8.0	
	Long.	52.9	73.0	8.5	47.9		67.6	8.5	
	Long.	52.9	72.6	8.0	49.8		69.8	10.5	
	Avg	53.0	72.7	8.2	49.5	0.68	68.2	9.0	94
-320	Trans.	51.1	70.9	7.0	47.7		69.8	8.5	
	Trans.	51.5	70.9	7.0	48.6		69.9	11.0	
	Avg	51.3	70.9	7.0	48.2	0.68	69.9	9.8	99
-423	Long.	60.7	84.3	7.0	54.8		79.5	6.5	
	Long.	60.1	81.6	5.0	53.9		75.8	5.5	
	Long.	60.3	84.7	6.0	56.5		76.6	6.0	
	Avg	60.4	83.5	6.0	55.1	0.66	77.3	6.0	93
-423	Trans.	59.7	80.5	4.0	49.6		82.8	5.5	
	Trans.	57.6	80.1	5.0	49.7		76.2	5.5	
	Avg	58.7	80.3	4.5	49.7	0.62	79.5	5.5	99

*Heliarc butt weld; x-rayed; roll planished; no doubler reinforcement

TABLE XIV

Mechanical Properties of 6061-T4 Aluminum Alloy

0.025" Sheet, Kaiser, QQ-A-327

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	30.8	40.7	17	40.1	
	Long.	30.4	40.2	17	41.9	
	Long.	30.5	40.5	17		
	Ave.	30.6	40.5	17	41.0	1.01
+78°F	Trans.	26.1	39.4	17	38.4	
	Trans.	26.5	39.9	17	38.9	
	Trans.				40.5	
	Ave.	26.3	39.7	17	39.3	0.99
-100°F	Long.	32.4	44.5	20	43.0	
	Long.	31.5	43.6	20	42.1	
	Long.	32.1	44.5	21	42.2	
	Ave.	32.0	44.2	20	42.4	0.96
-100°F	Trans.	29.0	43.7	22	42.3	
	Trans.	29.1	43.3	20	41.2	
	Ave.	29.1	43.5	21	41.8	0.96
-320°F	Long.	37.6	58.0	28	50.0	
	Long.	37.6	57.9	30	51.7	
	Long.	37.2	58.1	28	51.9	
	Ave.	37.5	58.0	29	51.2	0.88
-320°F	Trans.	33.1	57.2	30	50.5	
	Trans.	31.4	56.5	28	51.7	
	Ave.	32.3	56.9	29	51.1	0.90
-423°F	Long.	48.4	87.1	32	61.7	
	Long.	46.4	86.6	31	61.3	
	Long.	46.8	86.6	31	63.1	
	Ave.	47.2	86.8	32	62.0	0.72
-423°F	Trans.	44.4	92.5	34	62.0	
	Trans.	42.8	92.1	34	63.1	
	Ave.	43.6	92.3	34	62.6	0.68

TABLE XVI

Mechanical Properties of 6061-T6 Aluminum Alloy

0.020" Sheet, Kaiser, QQ-A-327

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	43.8	47.9	11	49.2	
	Long.	43.4	47.2	11	49.5	
	Long.	43.4	47.2	10	50.1	
	Ave.	43.5	47.4	11	49.6	1.05
+78°F	Trans.	41.6	46.4	10	48.0	
	Trans.	41.6	46.4	10	49.0	
	Ave.	41.6	46.4	10	48.5	1.05
-100°F	Long.	45.1	51.5	11	53.2	
	Long.	45.7	51.7	11	53.8	
	Long.	45.9	51.8	11	53.5	
	Ave.	45.6	51.7	11	53.5	1.04
-100°F	Trans.	44.4	51.0	11	51.6	
	Trans.	44.6	51.5	11	51.6	
	Ave.	44.5	51.3	11	51.6	1.01
-320°F	Long.	51.4	62.1	17	61.6	
	Long.	50.7	61.4	12	61.9	
	Long.	51.7	62.9	17	63.3	
	Long.	50.9	62.6	17		
	Ave.	51.2	62.3	16	62.3	1.00
-320°F	Trans.	47.2	60.9	12	60.1	
	Trans.	49.0	61.2	17	53.9	
	Trans.	49.2	60.6	18	59.6	
	Trans.				59.5	
	Ave.	48.5	60.9	16	58.3	0.96
-423°F	Long.	56.1	79.0	24	72.7	
	Long.	54.0	82.7	25	75.3	
	Long.	54.6	77.6	25	77.3	
	Long.	–	81.1	19	73.0	
	Ave.	54.9	80.1	23	74.6	0.93
-423°F	Trans.	55.0	77.9	25	71.3	
	Trans.	–	71.0	25	70.2	
	Trans.	54.7	78.3	25		
	Ave.	54.9	75.7	25	70.8	0.94

TABLE XVI

Mechanical Properties of 6061-T6 Aluminum Alloy

1" Plate, Kaiser, QQ-A-327

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	R.A. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	44.1	48.4	20	31	70.3	
	Long.	44.1	48.1	19	35	70.2	
	Long.	43.8	47.8	19	47	70.6	
	Ave.	44.0	48.1	19	38	70.4	1.46
+78°F	Trans.	71.6	81.2	10	9	71.1	
	Trans.	71.4	81.5	10	11	65.8	
	Ave.	71.5	81.4	10	10	68.5	0.84
-100°F	Long.	46.4	52.2	21	45	76.2	
	Long.	47.1	52.9	21	43	75.3	
	Long.	-	52.5	22	43	75.6	
	Ave.	46.8	52.5	21	44	75.7	1.44
-100°F	Trans.	73.0	84.7	6	6	75.6	
	Trans.	76.8	84.7	6	6	75.3	
	Ave.	74.9	84.7	6	6	75.5	0.89
-320°F	Long.	-	63.8	25	46	86.0	
	Long.	52.1	64.3	25	37	85.9	
	Long.	52.4	64.4	24	37	86.2	
	Ave.	52.3	64.2	25	40	86.0	1.34
-320°F	Trans.	83.7	94.0	4	3	86.9	
	Trans.	81.7	89.7	2	4	75.4	
	Ave.	82.7	91.9	3	4	81.2	0.88
-423°F	Long.	54.8	79.8	29	39	96.1	
	Long.	56.5	81.1	28	33	98.0	
	Long.	56.0	79.9	29	40	95.7	
	Ave.	55.8	80.3	29	37	96.6	1.20
-423°F	Trans.	94.6	102	3	2	94.6	
	Trans.	95.5	102	3	2	88.2	
	Ave.	95.1	102	3	2	91.4	0.90

TABLE XVII

Mechanical Properties of 7075-T6 Aluminum Alloy

0.025" Sheet, Alcoa, QQ-A-283

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°	Long.	71.8	79.8	9	80.6	
	Long.	68.9	79.0	9	82.2	
	Long.	-	79.8	9	81.4	
	Ave.	70.4	79.5	9	81.4	1.02
+78°F	Trans.	69.4	77.7	10	77.9	
	Trans.	69.4	77.4	10	77.2	
	Ave.	69.4	77.6	10	77.6	1.00
-100°F	Long.	75.7	84.3	10	84.6	
	Long.	76.7	85.3	10	83.7	
	Long.	76.2	85.6	11	85.5	
	Ave.	76.2	85.1	10	84.6	0.99
-100°F	Trans.	74.0	82.7	11	80.5	
	Trans.	74.2	83.7	7	80.7	
	Ave.	74.1	83.2	9	80.6	0.97
-320°F	Long.	86.5	97.2	10	76.0	
	Long.	86.5	97.2	10	72.9	
	Long.				78.2	
	Ave.	86.5	97.2	10	75.7	0.78
-320°F	Trans.	81.6	94.7	11	74.3	
	Trans.	82.0	95.1	12	73.5	
	Ave.	81.8	94.9	12	73.9	0.78
-423°F	Long.	98.3	116	8	83.7	
	Long.	106	117	6	84.2	
	Long.	95.7	114	9	85.0	
	Ave.	100	116	8	84.3	0.73
-423°F	Trans.	96.6	111	11	79.1	
	Trans.	-	112	13	78.3	
	Ave.	96.6	112	12	78.7	0.70

TABLE XVIII

Mechanical Properties of 7075-T6 Aluminum Alloy

2.5" Plate, Kaiser, QQ-A-283

TEST TEMP °F	DIRECTION	F_{ty} ksi	F_{tu} ksi	e %	R. A. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	84.7	92.9	14	13	115	1.24
	Trans.	42.2	47.0	11	43	68.7	1.46
-100°F	Long.	84.4	98.5	8		116	1.18
-320°F	Long.	106	110	4	4	112	1.02
	Trans.	49.9	61.9	26	36	86.2	1.39
-423°F	Long.	114	129	6	8	116	0.90

TABLE XIX

Mechanical Properties of 7079-T6 Aluminum Alloy

.080" Sheet, Kaiser

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	68.8	76.7	12	83.8	
	Long.	68.9	76.9	11	82.5	
	Long.	69.1	77.6	11		
	Ave.	68.9	77.1	11	83.2	1.08
+78°F	Trans.	66.7	75.9	10	81.3	
	Trans.	66.6	76.0	11	81.1	
	Ave.	66.7	76.0	11	81.2	1.07
-100°F	Long.	72.9	81.4	12	85.6	
	Long.	73.1	81.9	12	83.7	
	Long.	73.5	81.3	13		
	Ave.	73.2	81.5	12	84.7	1.04
-100°F	Trans.	69.9	80.9	12	84.5	
	Trans.	69.4	81.0	12	83.4	
	Ave.	69.7	81.0	12	84.0	1.04
-320°F	Long.	82.0	94.5	15	91.3	
	Long.	82.4	94.3	16	91.0	
	Long.	81.8	94.2	16		
	Ave.	82.1	94.3	16	91.2	0.97
-320°F	Trans.	78.2	94.0	11	80.1	
	Trans.	79.1	93.6	13	84.0	
	Ave.	78.7	93.8	12	82.1	0.88
-423°F	Long.	90.9	112	8	81.2	
	Long.	90.8	110	8	76.0	
	Long.	91.6	113	7		
	Ave.	91.1	112	8	78.6	0.70
-423°F	Trans.	89.4	105	6	78.5	
	Trans.	91.6	120	6	77.1	
	Ave.	90.5	113	6	77.8	0.69

TABLE XX

Mechanical Properties of 7079-T6 Alloy

5" Billet, Aluminum Company of America, 0-01041

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	R.A. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	70.8	77.9	11	17	91.1	
	Long.	66.5	74.7	10	17	97.0	
	Long.	70.9	77.9	12	16	94.0	
	Long.	64.0	73.7	12	17	96.5	
	Long.	71.6	78.6	10	11	87.3	
	Long.	64.2	73.9	12	11	97.5	
	Long.					87.9	
	Ave.	68.0	76.1	11	15	93.0	1.22
+78°F	Trans.	68.1	77.6	7	11	87.2	
	Trans.	63.1	73.1	8	12	89.3	
	Trans.	63.9	75.7	7	9	90.3	
	Trans.	62.9	74.2	10	8	89.9	
	Ave.	64.5	75.2	8	10	89.2	1.19
-100°F	Long.	71.5	79.6	3	8	84.8	
	Long.	69.2	78.1	4	8	88.3	
	Long.	71.3	78.4	3	8	83.2	
	Long.	68.9	78.5	4	9	80.6	
	Ave.	70.2	78.7	4	8	84.2	1.07
-100°F	Trans.	66.0	77.2	5	9	79.9	
	Trans.	68.5	73.8	3	8	72.6	
	Ave.	67.3	75.5	4	9	76.3	1.01
-320°F	Long.	-	85.5	-	2	78.2	
	Long.	79.2	87.1	2	4	68.1	
	Long.	85.4	89.3	4	2	77.6	
	Long.	84.1	89.3	3	3	83.2	
	Long.	85.9	87.8	3	2	71.5	
	Long.	-	87.9	3	2	79.0	
	Long.	84.0	90.0	3	2	77.1	
	Long.	85.4	88.5	2	3	71.6	
	Ave.	84.0	88.2	3	3	75.8	0.86
-320°F	Trans.	71.3	83.6	2	2	68.7	
	Trans.	77.1	82.4	2	1	63.1	
	Trans.	73.8	82.0	4	3	77.6	
	Trans.					70.3	
	Ave.	74.1	82.7	3	2	69.9	0.85
-423°F	Long.	80.7	91.5	3	3	74.9	
	Long.	90.8	98.2	2	4	69.7	
	Long.	-	90.1	1	3	59.4	
	Long.	91.1	97.8	3	3	48.5	
	Long.					70.4	
	Ave.	87.5	94.4	2	3	64.6	[illegible]
-423°F	Trans.	88.3	[illegible]	1	2	[illegible]	
	Trans.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
	Ave.	[illegible]	[illegible]	1	[illegible]	[illegible]	[illegible]

TABLE XXI

Mechanical Properties of 7178-T6 Aluminum Alloy

0.036" Sheet, Kaiser, MIL-A-9180A

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	82.4	90.2	12	91.4	
	Long.	82.6	89.6	12	93.3	
	Long.	83.0	90.0	12	90.7	
	Ave.	82.7	89.9	12	91.8	1.02
+78°F	Trans.	79.9	90.2	11	79.5	
	Trans.	80.1	90.5	11	88.5	
	Ave.	80.0	90.4	11	84.0	0.93
-100°F	Long.	87.8	95.3	11	81.0	
	Long.	88.2	95.2	11	75.0	
	Long.	87.5	95.0	11	74.5	
	Ave.	87.8	95.2	11	76.8	0.81
-100°F	Trans.	82.8	95.4	10	81.9	
	Trans.	84.1	95.9	10	66.4	
	Trans.				74.5	
	Ave.	83.5	95.7	10	74.3	0.78
-320°F	Long.	98.6	106	4	59.5	
	Long.	98.9	106	4	57.2	
	Long.	98.8	107	5	51.9	
	Long.				61.8	
	Ave.	98.8	106	4	57.6	0.54
-320°F	Trans.	94.5	106	3	55.4	
	Trans.	92.2	106	3	54.3	
	Trans.				46.0	
	Ave.	93.4	106	3	51.9	0.49
-423°F	Long.	112	122	2	68.3	
	Long.	114	125	2	57.5	
	Long.	108	122	2	61.2	
	Long.	111	122	3	63.9	
	Ave.	111	123	2	62.7	0.51
-423°F	Trans.	112	125	3	56.9	
	Trans.	111	123	3	54.1	
	Trans.				59.1	
	Ave.	112	124	3	56.7	0.46

TABLE XXII

Mechanical Properties of X7275-T6 Aluminum Alloy

0.050" Sheet, Kaiser, Experimental Heat

TEST TEMP.	DIRECTION		F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.		75.7	87.0	14	90.9	
	Long.		75.1	86.0	14	90.7	
	Long.		76.5	86.6	14	91.3	
		Ave.	75.8	86.5	14	91.0	1.05
+78°F	Trans.		72.4	83.7	14	89.7	
	Trans.		72.7	83.4	14	89.5	
		Ave.	72.6	83.6	14	89.6	1.07
-100°F	Long.		75.5	86.4	15	95.4	
	Long.		76.2	84.5	15	95.7	
	Long.		75.2	84.7	15	94.6	
		Ave.	75.6	85.2	15	95.2	1.12
-100°F	Trans.		71.9	83.2	14	89.8	
	Trans.		74.7	84.1	14	91.4	
		Ave.	73.3	83.7	14	90.6	1.08
-320°F	Long.		86.1	95.0	7	87.4	
	Long.		87.5	99.4	5	76.6	
	Long.		81.1	94.6	6	71.9	
		Ave.	84.9	96.3	6	78.6	0.82
-320°F	Trans.		76.5	93.3	11	79.1	
	Trans.		83.7	99.1	6	84.7	
		Ave.	80.1	96.2	9	81.9	0.85
-423°F	Long.		97.9	116	5	76.1	
	Long.		98.9	111	4	75.0	
	Long.					74.8	
		Ave.	98.4	114	5	75.3	0.67
-423°F	Trans.		93.5	106	4	81.2	
	Trans.		96.8	109	4	82.0	
		Ave.	95.2	108	4	81.6	0.76

TABLE XXIII

Material Selection Guide

(An X Indicates the Material May Be Used For Structural Applications at the Indicated Temperature)

Material	Temperature +78°F	-100°F	-320°F	-423°F
2014-T6 Sheet	X	X	X	X
2024-T3 Sheet	X	X	X	
2024-T4 Sheet	X	X	X	X
2024-T4 Plate	X	X	X	X
2219-T81 Sheet	X	X	X	X
2219-T87 Sheet	X	X	X	X
5052-H38 Sheet	X	X	X	X
5083-H38 Sheet	X	X	X	X
5086-H34 Sheet	X	X	X	
5086-H38 Sheet	X	X	X	
5154-H38 Sheet	X	X	X	
5456-H343 Sheet	X			
6061-T4 Sheet	X	X	X	
6061-T6 Sheet	X	X	X	X
6061-T6 Plate	X	X	X	X
7075-T6 Sheet	X	X		
7075-T6 Plate	X	X		
7079-T6 Sheet	X	X	X	
7079-T6 Billet	X	X		
7178-T6 Sheet	X			
7275-T6 Sheet	X	X		

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